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IEC 61850 based digital communication as interface to the primary equipment

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1. INTRODUCTION

During the past years, the IEC TC57 defined the IEC 61850 standard for "Communication Networks and Systems in Substations". This standard is now ready to be used, not only between the station level computer and the bay level devices, but also for the open communication to the primary equipment.

In the past, a typical SA system contained a station bus connecting the bay level equipment (relays, bay controllers) with the station level equipment. IEC 61850 not only standardizes the communication technology used in conjunction with the station-/interbay bus, but also facilitates universal SA modeling [1]. Digital communication interfaces to the process level are additional benefits of the IEC 61850. The digital communication will replace traditional wiring between the bay level devices on one side and the instrument transformers and switchgear apparatuses on the other side [2]. Product standards for primary equipment using these new interfaces already exist or are under preparation.

IEC 61850 uses mainstream communication technologies like switched Ethernet and TCP/IP. The benefit of this choice is, that commonly available and accepted communication components can be used. However, while the use of Ethernet for the communication between station and bay level does not seem to create any problems, it needed to be verified that the same technology can be used for the more time critical communication between the control and protection devices and the primary apparatuses.

The paper gives an overview of the feasibility studies made with IEC 61850 in the process-close area.

KEYWORDS
IEC 61850 – Substation Automation – Station Bus – Process Bus – SV – GOOSE – MMS – Ethernet – Stack – Feasibility Study

2. COMMUNICATION REQUIREMENTS

2.1 Main types of communication within a substation

Figure 1 illustrates the main communication services and paths within a substation automation system according to IEC 61850.
The communication services available on the station-/interbay level are also required for the communication to process-close devices (intelligent circuit breaker and disconnector controllers, non-conventional current and voltage transducers and other sensors). This includes operating information (status indications, control, measured values) as well as configuration information (file transfer, parameteri-

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zation). However, the nature of the process-close devices adds two additional and very demanding types of data transfer [3]:

- The transmission of sampled voltage and current values from the transducers results in a large amount of data sent in a more or less continuous stream. These data must be transmitted with a maximum delay of no more than four milliseconds to avoid exceeding the round trip delay of a pure conventional SA system solution. The transmission rate must meet the requirements of the receiving applications. For simple definite-time overcurrent protection applications or calculation of some r.m.s. values, transmission rates of a few hundred sampled values per second are sufficient. But for high-order protection or revenue metering scan frequencies of several kilohertz' are required.
- The transmission of trip commands and blocking signals for the mutual interlocking requires high reliability and speed in the order of a few milliseconds. The transmission of this information shall not be influenced by other data flows.

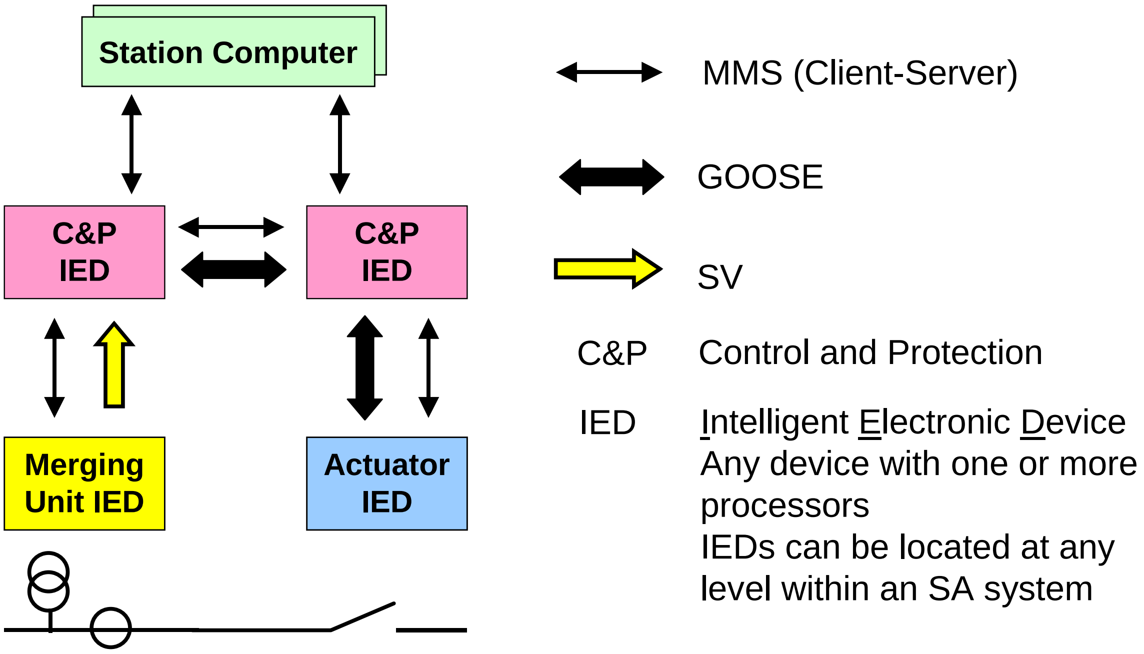


Figure 1: Main types of IEC 61850 communication services

This results in a total of three communication categories with the following transmission capabilities:

- SV (Sampled Values): Voltage and current samples from transducers demand large amounts of standardized, high priority, cyclical data throughput.
- GOOSE (Generic Object Oriented Substation Event): Trip commands and interlocking information have standardized, high priority, reliable and safe transmission needs.
- MMS (Manufacturing Message Specification): Most operational information can be transmitted with standard, medium priority and safe procedures. Device specific information is of low priority, depends on proprietary but self-descriptive entities.

2.2 Time synchronization requirements

Today, most devices in a substation demand clock synchronization. With the introduction of the IEC 61850 based communication solution and the MU (merging unit) systems in a substation, all devices connected to the network must be synchronized. The synchronization precision depends on the device specific applications. Generally the synchronization accuracy is more demanding the further down one goes in the substation automation system hierarchy. The station level requires an accuracy of a few hundred milliseconds to display the time of an activity to the operator. The bay level control and protection devices require generally one half to one millisecond of accuracy for the time stamping of events. But the MU systems on the process level require a few microseconds of accuracy for the synchronous sampling of the measured analogue values.

Using available, standard Ethernet controllers, clock precision of about 100 µs can be achieved. Synchronization of the sampled analog values – the required accuracy is some 5 µs there - via Ethernet using standard components is not yet possible today. For the time being, a separate bus for synchronization (PPS, Pulse Per Second) must be introduced. Newest investigations in the area of Real-Time Ethernet (see IEEE 1588, IEC TC65 et al) have led to solutions, which allow synchronization directly over the Ethernet but with the drawback of using specialized hardware components. The breakthrough of real-time or industrial Ethernet in the near future will lead to a broad range of commercially available products here.

3. COMMUNICATION STACK

As discussed earlier, the different services have different real time requirements. IEC 61850 specifies therefore that only the less time critical MMS communication is based on the standard TCP/IP, while SV and GOOSE communication are directly mapped to the Ethernet layer (see figure 2). The prioritization layer ensures that outgoing SV and GOOSE frames are marked as high priority frames and that these frames are handled with priority within all participating IEDs.

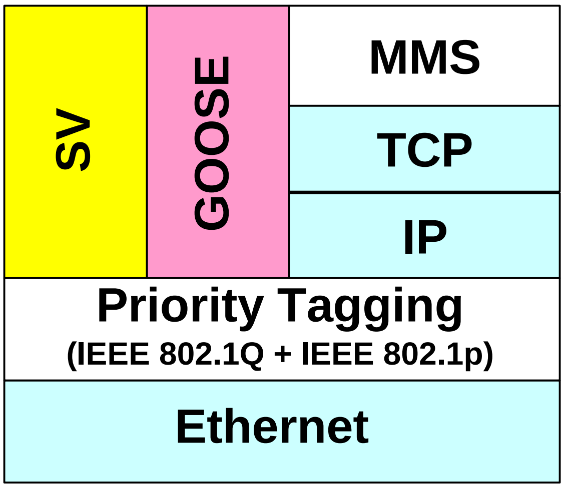


Figure 2: IEC 61850 overall communication stacks

3.1 MMS stack

The MMS stack provides a robust, connection-oriented communications capability supporting standardized object models and communication services over a TCP/IP communications scheme. The MMS stack must manage potentially large object models and a highly dynamic range of inputs within the resource (memory, processing time, and scheduling) constraints of the platform. The specific resource requirements depend on the complexity of the object model, but are usually contained within the range of a wide variety of embedded platforms. The connection reliability is maintained by the use of RFC 1006 specification over the TCP/IP protocol suite. This requires an efficient TCP/IP implementation that can operate in a packet-oriented manner, and with the Keep-Alive Acknowledgement connection maintenance scheme set to a relatively short (for TCP/IP) duration.

3.2 GOOSE stack

The GOOSE stack requires access to a low-level Ethernet packet interface. The Ethernet interface must support efficient multicast operation. Hardware address filtering minimizes the impact on system resources, but may not be available on all devices for an arbitrarily large number of multicast addresses. Since the GOOSE frames are ASN.1 BER encoded, the stack has to encode/decode the frames according to a static or a dynamic frame configuration.

3.3 SV stack

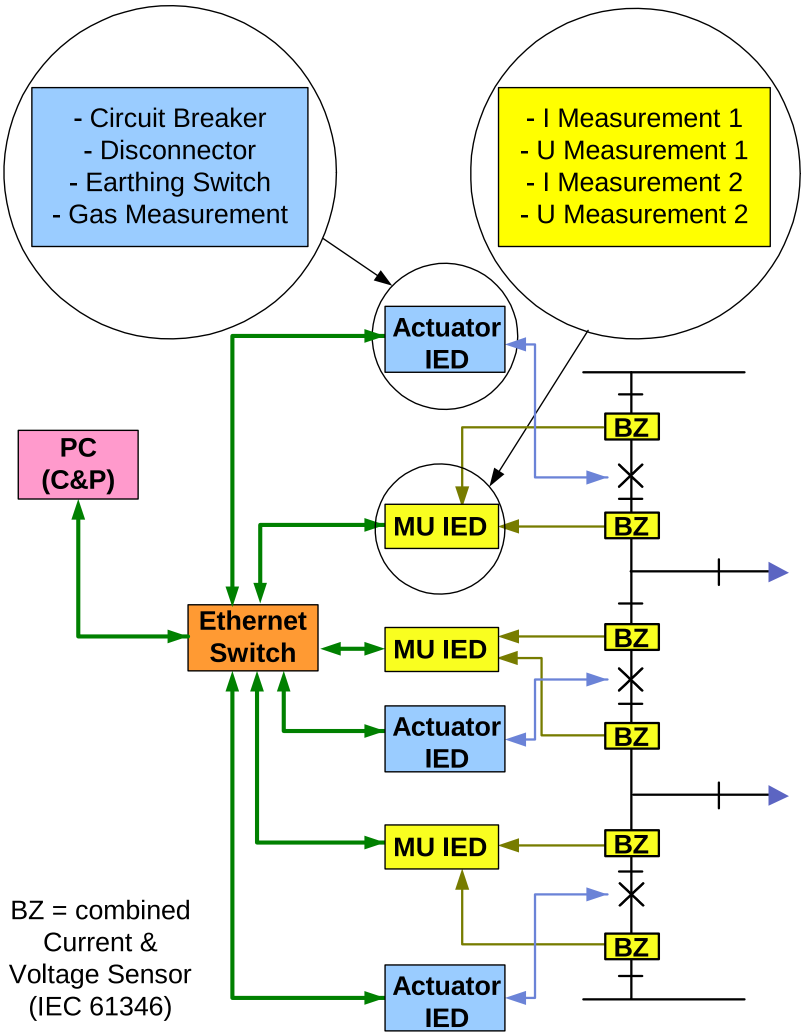
Compared to the above, the stack required for SV is quite simple: IEC 61850-9-1 uses a fixed dataset containing four currents and four voltages. For the IEC 61850-9-2, on the other hand, the publisher and the subscribers have to configure themselves according to the dataset definition found, e.g., in the substation's configuration file. As this has only to be done during start-up, highly efficient run-time code can be written.

4. FEASIBILITY INVESTIGATIONS

As already mentioned, special attention has to be given to the time critical communication between the control/protection and the primary equipment. This is especially the case for the transmission of sampling data (SV) from voltage and current transducers to the bay level functions, and for the transmission of trip commands back to the circuit breakers. It had to be verified that Ethernet frames are not delayed more than allowed, that frames are not lost within Ethernet components like switches, and that IEDs are not overloaded by the handling of Ethernet frames.

IEC 61850 provides and proposes several mechanisms and techniques to solve these issues (e.g. switched Ethernet, priority tagging etc.). When using these techniques, in theory, a high degree of predictability can be achieved. A number of feasibility tests have been defined to experimentally demonstrate that these issues are uncritical, that the entire SA specific communication requirements are met, and that it is possible and economical to integrate the communication stacks into IEDs. Also, a detailed study was done to check if the flexibility given by IEC 61850-9-2 would significantly increase the IED's CPU load or the transmission times compared to fixed frame formats like IEC 61850-9-1.

4.1 Test environment and test principle



For the feasibility tests the following equipment was used:

- Three actuator IEDs performing several different roles. The IEDs are PowerPC based prototyping boards with a 100/10 Mbps Ethernet interface, running VxWorks and the IEC 61850 communication stacks (MMS and GOOSE from Tamarack, SV from ABB), and IEC 61850-9-1/-9-2 decoder software.
- Three MU IEDs used as IEC 61850-9-1/-9-2 sources.
- Ethernet switches from different vendors
- Ethernet Analysers and PCs used as C&P IED with MMS client software from Tamarack.

Figure 3: Modeled substation and IED allocation

The tests simulated the IEDs and the network traffic within a diameter of a 1½ breaker arrangement (see figure 3). The Actuator IEDs were configured during startup by reading a preloaded SCL (Substation Configuration Language, IEC 61850-6) file and by reading a set of configuration switches. Based on that information, the boards configure themselves to perform the expected task(s) of the test being executed. After test-start, the boards are time-stamping sent and received frames on the application layer and the Ethernet driver (physical) layer (see figure 4). Time stamping accuracy between the boards is better than ±20 µs.

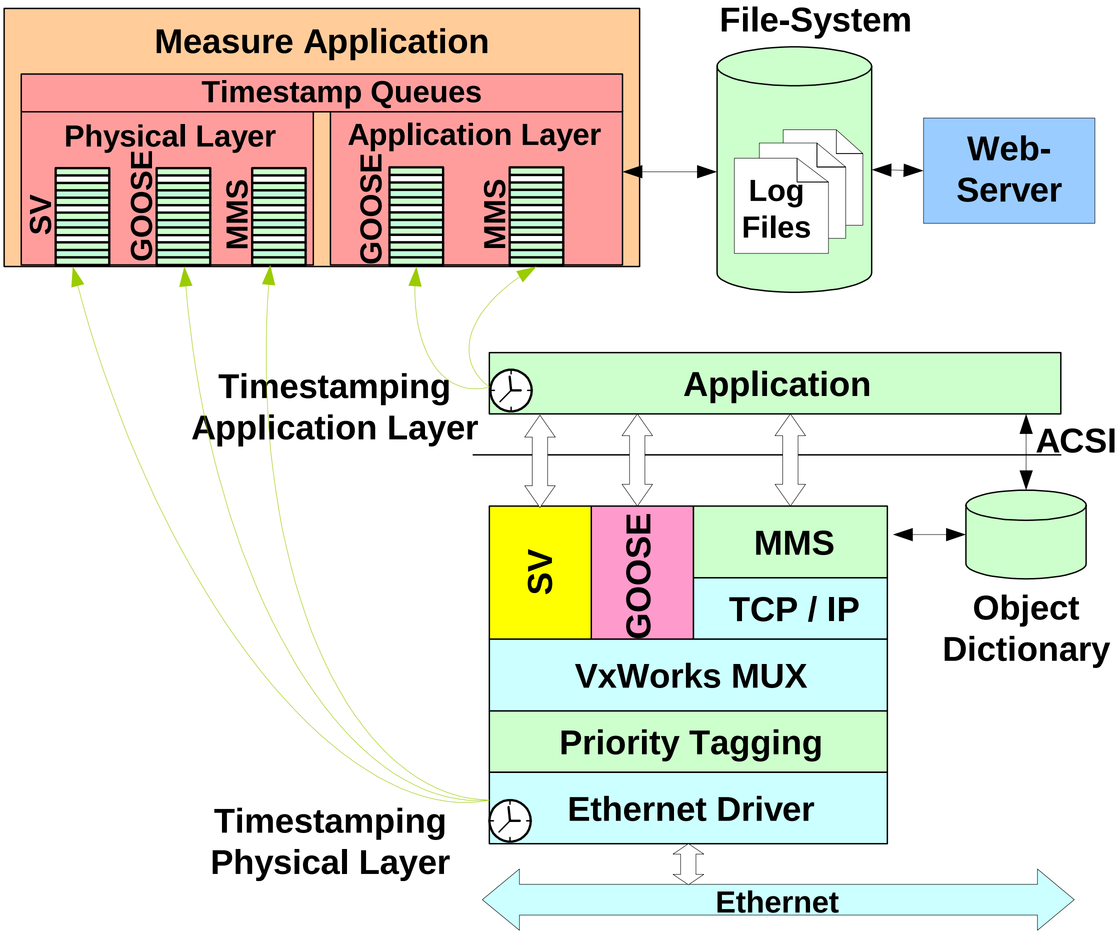


Figure 4: Actuator IED software architecture and time stamping mechanism

Depending on the type of the test, the chosen test duration had to be varied between some minutes and several hours. The test results were stored in the IED's internal file system and transferred via an integrated web-server to the office PC environment. Result evaluation was performed automatically. In a first phase the three different communication mechanisms (SV, GOOSE and MMS) were investigated separately. This was followed by a second phase where the entire network behavior for real life situations and for simulated overload situations was analyzed.

4.2 Test of SV communication

In this basic test the combined SV transmission time and switch delays were measured.
Table I lists the delays for IEC 61850-9-1 and for IEC 61850-9-2 in a situation without additional network load.

Table I: Time delays of different IEC 61850-9 versions

IEC 61850-9 Version	Average Delay (μs)					
	Sampling + Filtering	MU: Encoding + Sending	Transmit (10 MBps)	Receiver: Decode	Total @10 Mbps	Total @100 MBps
9-1 IS	2'034	331	183	219	2'767	2'551
9-2 CDV	2'034	556	570	360	3'520	3'007
9-2 FDIS	2'034	350	407	260	3'051	2'685

When adding network load, the maximum transmission delays increase depending on the length of the frames. Since SV frames are marked as high priority frames, no further delays caused by other low priority traffic load was expected nor seen. However, it has been noticed that older Ethernet switches did not work properly if a low priority load of 100 % was applied. In that case, the switch has to discard some low priority frames. Older switches do not correctly perform this function.

4.3 Test of GOOSE communication

In this test, one prototyping board was sending GOOSE frames and a second one was receiving them. The test setup allowed to measure the runtime through the GOOSE stack code (IED pre-processing and IED post-processing) as well as the pure physical transmission time. Table II summarizes the observed results.

Table II: Time delay of GOOSE frames

Description	Link Speed 100 Mbps average (min … max)
IED Preprocessing	460 μs (440 … 810 μs)
Transmission	10 μs (0 … 38 μs)
IED Postprocessing	460 μs (430 … 510 μs)
Total	902 μs (862 … 1291 μs)

4.4 Test of MMS communication

In the MMS communication tests, a PC running a MMS client software was communicating with a MMS server. The transmission delay of a MMS request and the delay of the stack was measured.

Table III: Time delay of MMS frames

*) Small negative numbers may occur since the time stamp accuracy is ±20 μs.

Description	Link Speed 100 Mbps average (min … max)
Transmission	11 μs (-8 … 25 μs) *)
IED Postprocessing (MMS Server)	1399 μs (1350 … 3834 μs)
Total	1410 μs (1358 … 3848 μs)

The prototyping board software had not been designed to guarantee optimum MMS request response times (a lot of other tasks are operating at higher priorities). As a result, MMS responses were sometimes delayed up to 2.5 ms within the MMS server stack (see figure 5). In the used MMS stack version the ASN.1 BER decoding was implemented very optimized, but the object model processing was not. This has been changed in the meantime and therefore even faster response times can be measured.

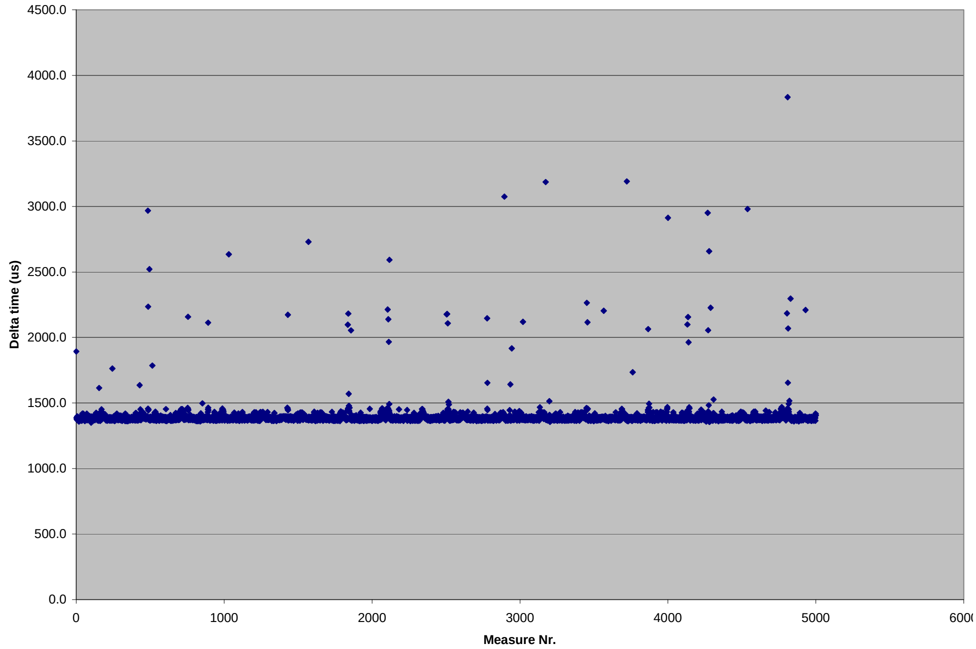


Figure 5: MMS server stack delay

4.5 Test of a complete setup

In these tests, the traffic in a full 1½-breaker diameter was simulated. Extra “stress load” was added to the basic normal load by using an Ethernet analyzer as load generator. The following figures show the impact of 50 % extra network load (50 % of 100 Mbps, non-prioritized multicast frames with a length of 64 bytes) on the complete SV sampling and transmission delay (figure 6) and the GOOSE transmission delay (figure 7).

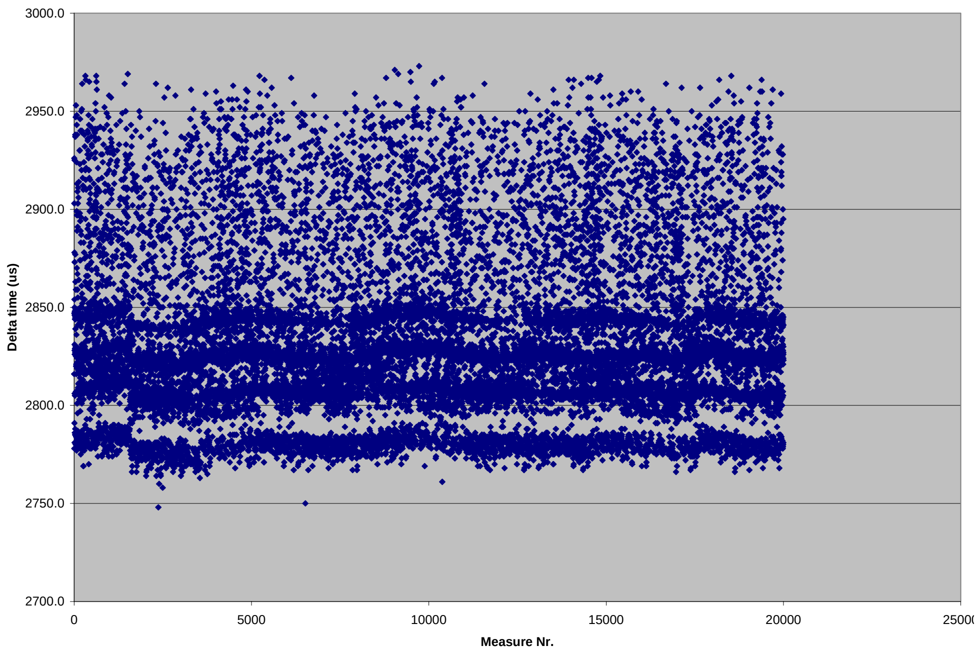


Figure 6: SV time delay (sampling + filtering, encoding + sending and transmission delay) in complete test setup; 50 % bus load

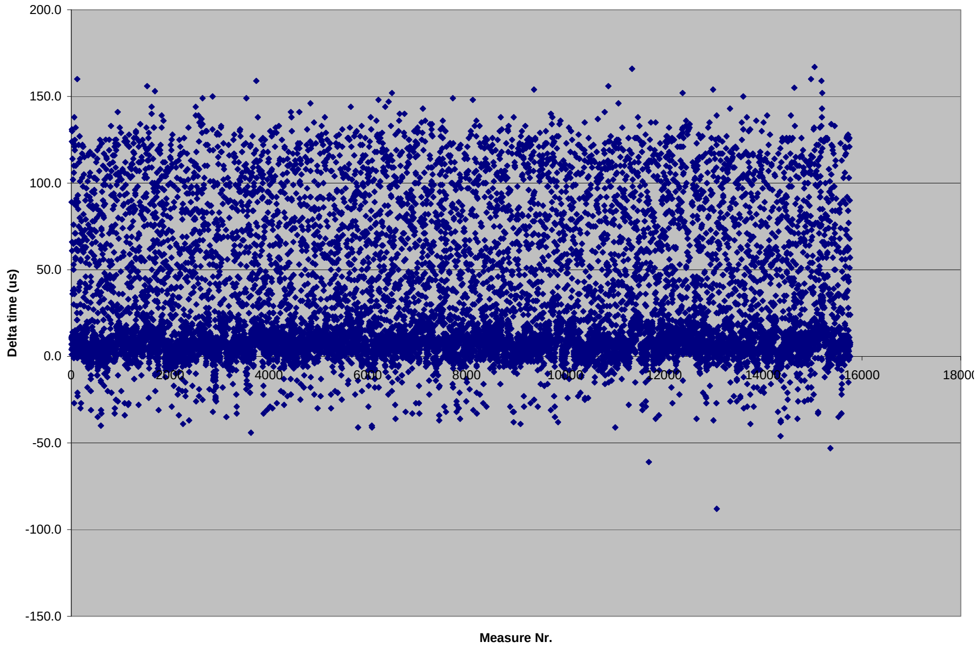


Figure 7: GOOSE transmission time delay in complete test setup; 50 % bus load

4.6 Hardware resources

The measurements have shown that the CPU capacity required to receive and decode incoming SV frames is the most demanding communication aspect. This is the case because analog samples are transferred with a high and regular repetition rate of 4 kHz or more. Also, typically more than one incoming sample data stream has to be processed. GOOSE frames are slightly more complicated to decode, but since the typical repetition rate is much smaller and decreasing over the time, the generated load is less critical. The load generated by handling the MMS communication is not negligible, but since less important and time critical information is exchanged, the priority of the related tasks can be kept low. The used stacks including the modeled nodes, objects and communication services – like Get and Set, control, reporting and logging – require approximately 600 kB of memory.

5. CONCLUSIONS and FURTHER WORK

The results of the feasibility investigations show that the communication approach as proposed by IEC 61850 fulfils the real-time requirements of control and protection. However, for correct operation, attention must be given to certain vital parameters. System integrators have to think about the network topology and utilization and have to select state of the art industrial Ethernet switches. IED manufactures must keep in mind that an optimized communication interface design is necessary. However, these issues will become less important in the future since more and more advanced products and solutions are expected to be available in the industrial Ethernet market.

An issue not solved by the current mappings defined in IEC 61850 is the accurate time synchronization used for synchronous sampling. As soon as the solutions from the area of Real Time Ethernet activities are mature enough and implemented in commercially available products, the IEC TC57 WG10 will extend IEC 61850 with a mapping for accurate time synchronization over Ethernet.

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